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DESIGN OF AN ATTITUDE CONTROL SYSTEM FOR AN EARTH-SUN ORIENTED SATELLITE

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ABSTRACT

The design of an attitude control system for an earth-sun oriented satellite is presented. The attitude control system is intended for use on the Orbiting Geophysical Observatories being developed by Space Technology Laboratories, Inc. under Contract NAS5-899 with the NASA, Goddard Space Flight Center. The attitude control system maintains one body axis of the satellite in alignment with local vertical and utilizes the angular orientation of the satellite body about local vertical together with a single degree of freedom solar array to maintain the solar cells perpendicular to the sun's rays. The control law required to accomplish this orientation and the implication of this control law on the control equipment design are presented. All components of the attitude control system are in an advanced state of development and the performance of these components is discussed.

The satellite attitude is controlled so that a body fixed axis is pointed toward the center of the earth. Simultaneously, the satellite attitude about the local vertical is controlled so that a second body axis is perpendicular to the sun's rays. The solar array rotates about this second body axis and thereby provides the fourth degree of freedom necessary to simultaneously position the solar array perpendicular to the sun's rays while maintaining orientation relative to the earth's center. These simulataneous pointing requirements place response requirements on the attitude control system. However, the design of the attitude control system is relatively independent of control law considerations once the speed of response dictated by the control law is met. The control law presented is easily implemented.

The control components which comprise the attitude control system are described in detail. Error signals are generated by earth edge tracking scanners and a sun sensor. These error signals control the satellite by a combination of reaction wheels and constant thrust gas jets. In order to simplify the control system components to the greatest extent possible, on-off control of both the reaction wheels and the gas jets is utilized. Consistent with the concept of on-off control, magnetic amplifiers are utilized with the attendant increase in system reliability at only minor increase in total system weight. The mechanical solar array drive also operates in on-off fashion and utilizes a wabble drive which allows all high speed gearing and bearing stages to be hermetically sealed.

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ILLUSTRATIONS

1. INTRODUCTION

The operation of a communication satellite is greatly enhanced by controlling the attitude of the satellite so that a communications antenna can be pointed toward the earth. A further requirement on attitude control is imposed by the desire to orient a collection array toward the sun to produce electrical power. This paper describes the design and mechanization of a control system which satisfies these earth-sun pointing requirements. Since these orientation requirements also occur in the design of scientific satellites, the numerical examples presented in this paper are taken from a scientific satellite currently under construction at Space Technology Laboratories, Inc. This satellite, which is called the Orbiting Geophysical Observatory (OGO), is designed to operate in a wide variety of orbits including low altitude circular and highly eccentric orbits. The attitude control system for this satellite points one face of the satellite at the earth and orients flat solar cell arrays toward the sun. Since the OGO satellite must satisfy for a large variety of orbits the general communication satellite attitude control requirements, a description of the OGO attitude control system is instructive when considering the design of a communication satellite control system.

Section 2 of this paper describes the pointing requirements mathematically and deduces from these pointing requirements a satellite control law which satisfies the simultaneous earth-sun orientations. In Section 3, the mechanization of this control law is discussed, and Section 4 is devoted to a description of the equipment used for control. In the design of the OGO control system, emphasis has been placed on utilization of techniques to enhance system reliability. For this reason, the basic OGO control system is nonlinear of the off-on or bang-bang type. This mode of control is particularly adapted to magnetic amplifiers, and these components are used for the main power amplification required. Other portions of the control system include an infrared edge tracking horizon scanner, sun sensors, reaction wheels, and gas jets.

2. PERFORMANCE REQUIREMENTS

The function of the attitude control system is to keep one axis of the vehicle aligned at all times with the local vertical, while simultaneously maintaining a second axis (the solar array axis) perpendicular to the sun's rays.[1,2] Thus a planar array of solar cells can be rotated about the solar array axis for maximum energy collection. In this section the ideal control laws for this orientation are derived, and their effect upon system performance is discussed.

2.1 Coordinate Systems

Refer to Figure 1 for a definition of coordinate systems. In this figure the orbit plane is the X-Z plane with orbital rate directed along the Y axis. The location of the Z axis is chosen such that a unit vector from the center of the earth to the sun (μ_s) lies in the Y-Z plane. The satellite anomaly is measured from the Z axis and is denoted by α as shown. The X_r, Y_r, Z_r system is obtained from the Y, Y, Z system by means of this rotation through α. β is the angle between Y and μ_s.

The body coordinate system is defined in Figure 2. It is derived from the X_r Y_r Z_r system by the ordered rotations ψ, θ, and ϕ about Z_r, Y_2 and X_b respectively as pictured in Figure 3.

2.2 Ideal Control Laws

In terms of the coordinate systems previously defined, the ideal pitch and roll control laws can be stated quite simply as

$$\phi = \theta = 0$$

Given ideal pitch and roll control, the ideal yaw control law can be obtained by equating the component of μ_s which lies along the X_b axis to 0. This yields:

$$\psi = \psi_i = \tan^{-1} (\tan \beta \sin \alpha)$$

Given ideal pitch, roll, and yaw control, the ideal array angle can be derived in a similar fashion and is

$$\phi_a = \phi_{ai} = \sin^{-1} (\sin \beta \cos \alpha)$$

1 Superscripts refer to references in the bibliography.

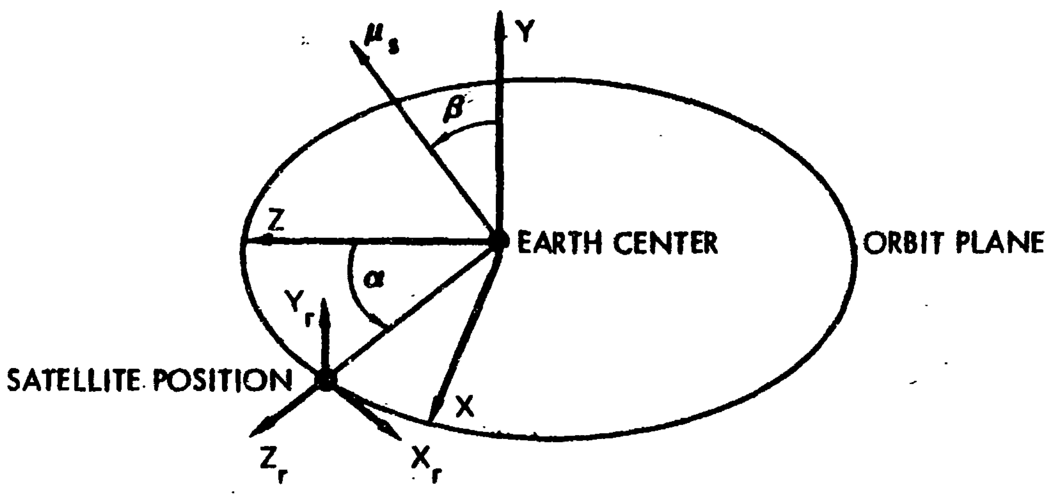


Figure 1 - ORBIT COORDINATE SYSTEM

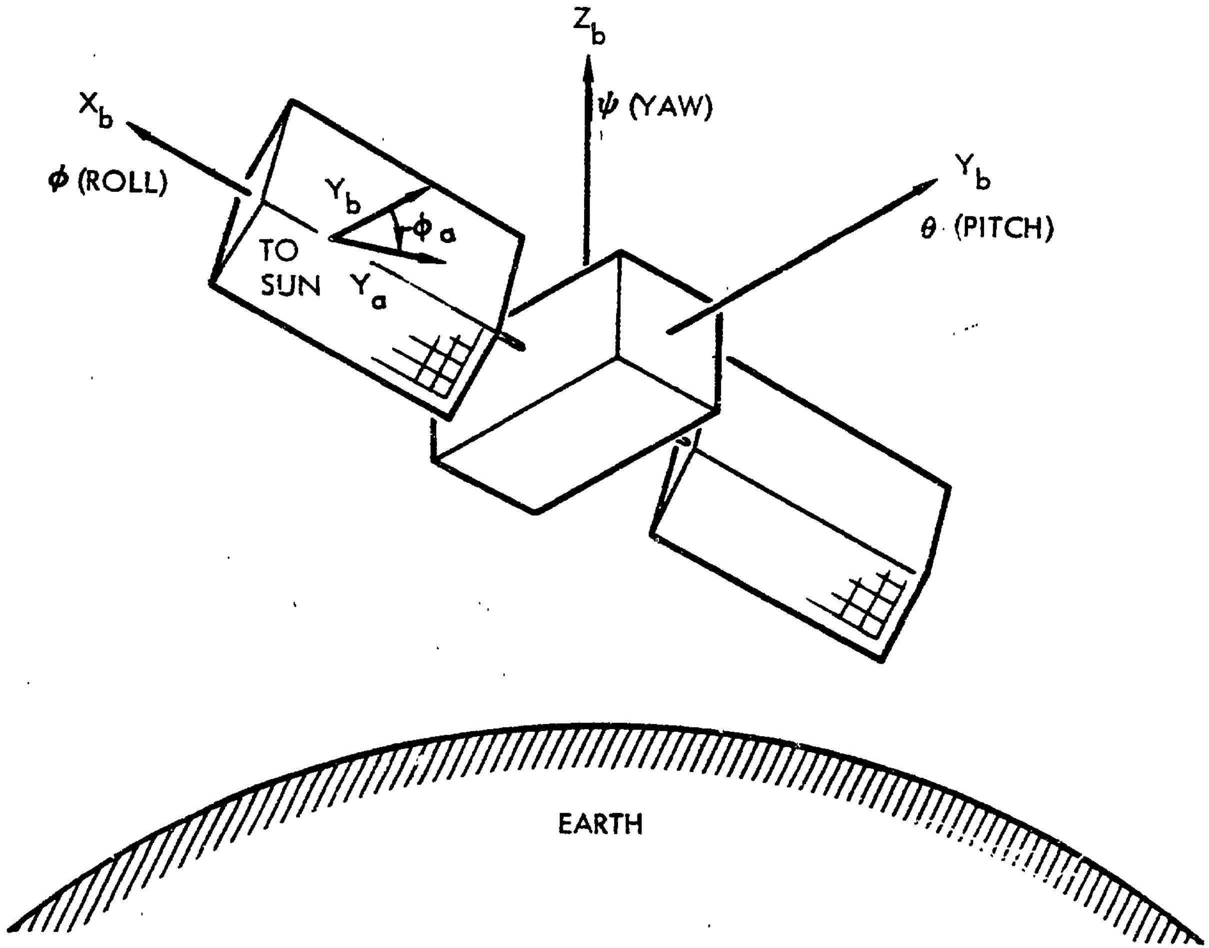


Figure 2 - BODY COORDINATE SYSTEM

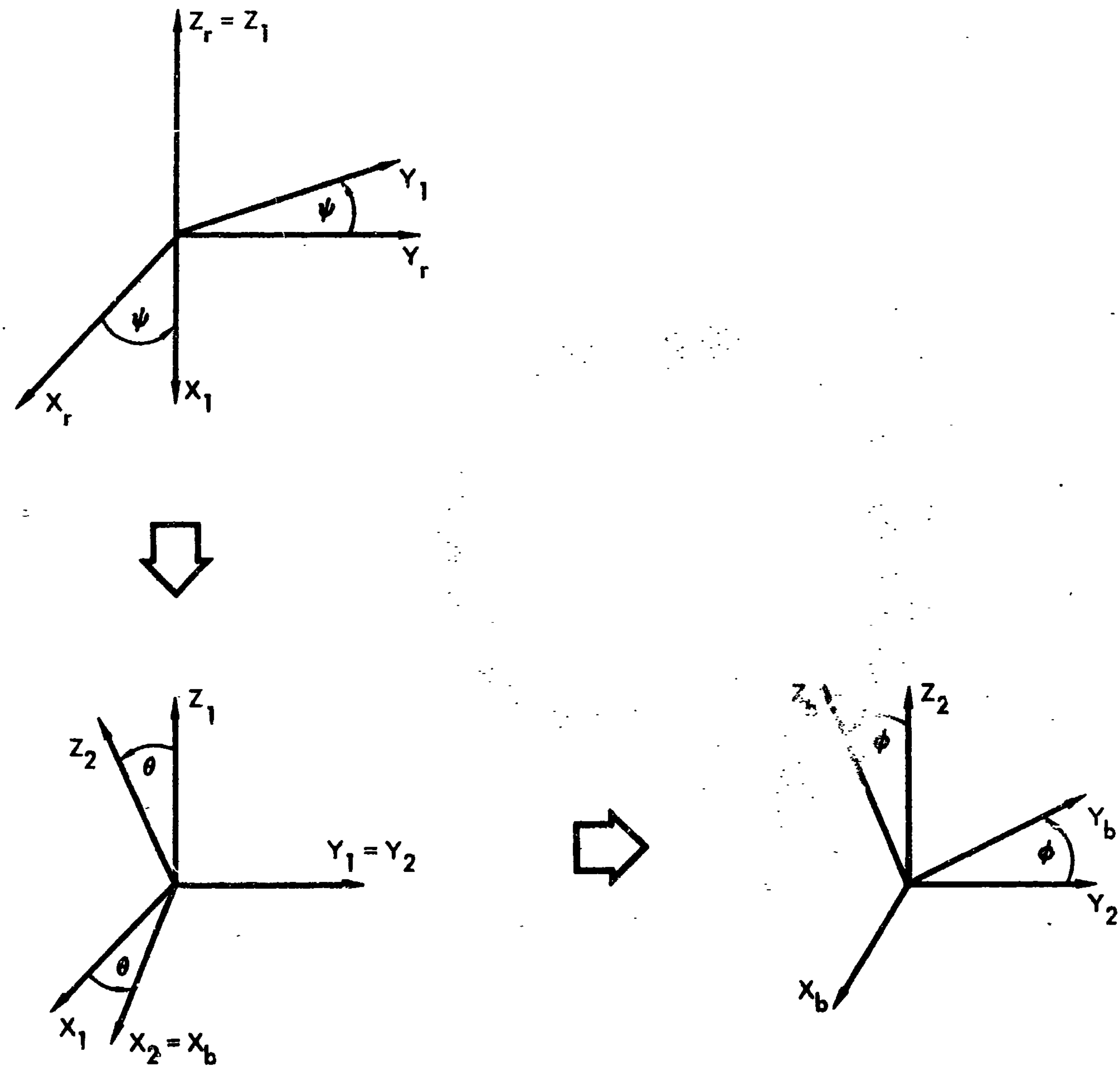


Figure 3 - ROTATIONS FROM REFERENCE COORDINATE SYSTEM
TO BODY COORDINATE SYSTEM

A plot of ψ_i versus α is given in Figure 4 with β as a parameter, and a plot of ϕ_{ai} versus α is given in Figure 5.

Given ideal attitude control, the component of angular velocity along the X body axis, ω_{xb}, is given by

$$\omega_{xb} = \dot{\alpha} \sin \psi_i ,$$

the component of angular velocity along the Y body axis, ω_{yb} is given by

$$\omega_{yb} = \dot{\alpha} \cos \psi_i .$$

the component of angular velocity along the Z body axis is given by

$$\omega_{zb} = \dot{\psi}_i = \frac{\dot{\alpha}(\cos \beta \sin \beta \cos \alpha)}{1 - \sin^2 \beta \cos^2 \alpha} ,$$

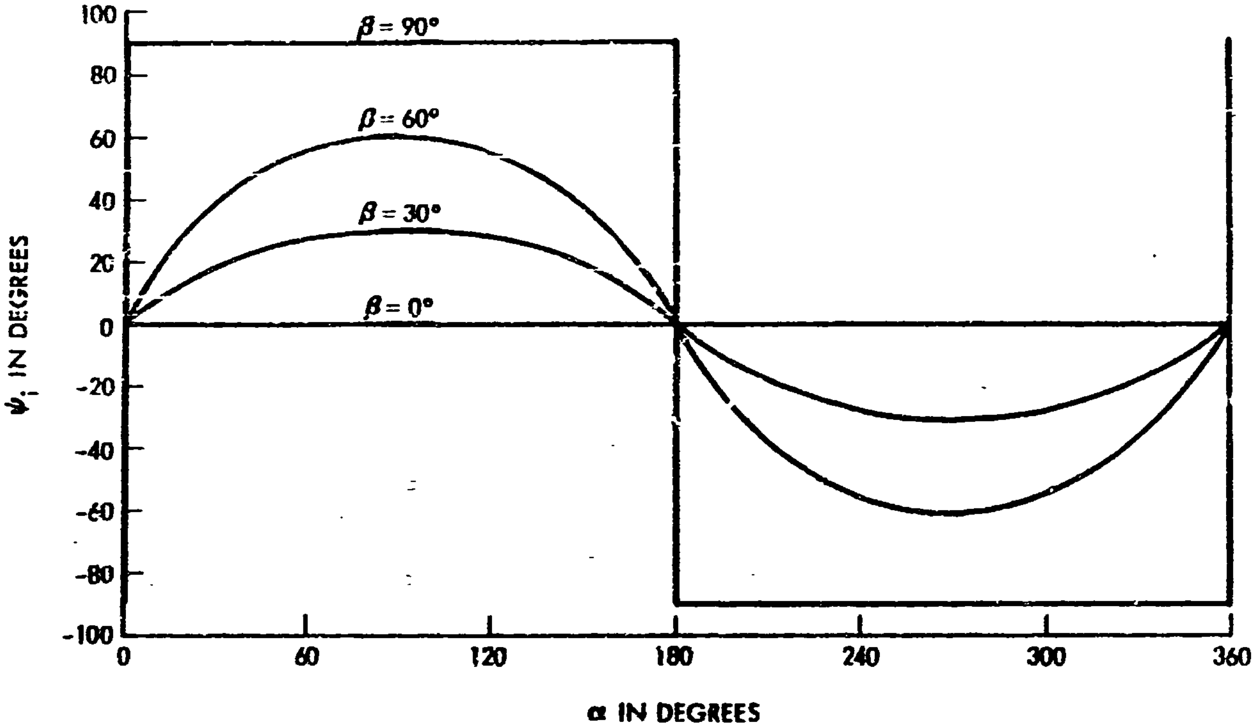
and the ideal angular velocity of the solar array with respect to the body is given by

$$\dot{\phi}_{ai} = \frac{\dot{\alpha} \sin \alpha}{\left[\frac{1}{\sin^2 \beta} - \cos^2 \alpha\right]^{\frac{1}{2}}}$$

2.3 Design Constraints

As indicated in the previous equations, the most stringent attitude control requirements are imposed when $\beta = 90^{\circ}$ and $\alpha = 0$. This condition occurs when the earth, satellite and sun are directly in line and is termed the "noon" condition. At this time, the nominal values of yaw rate, yaw acceleration, pitch acceleration, and roll acceleration are all infinite.[3] Obviously the vehicle cannot be designed to perform this maneuver exactly.

A comparison condition to the noon region is eclipse of the sun by the earth. Upon entering an eclipse the yaw reference and the solar array reference are lost. Upon emerging from eclipse, the vehicle can, in general, have any yaw position along with a large error in array angle. Therefore, to follow the ideal control law upon emergence from eclipse would again require



NOTE: ONLY PRINCIPAL ANGLES ARE SHOWN

Figure 4 - IDEAL YAW ANGLE

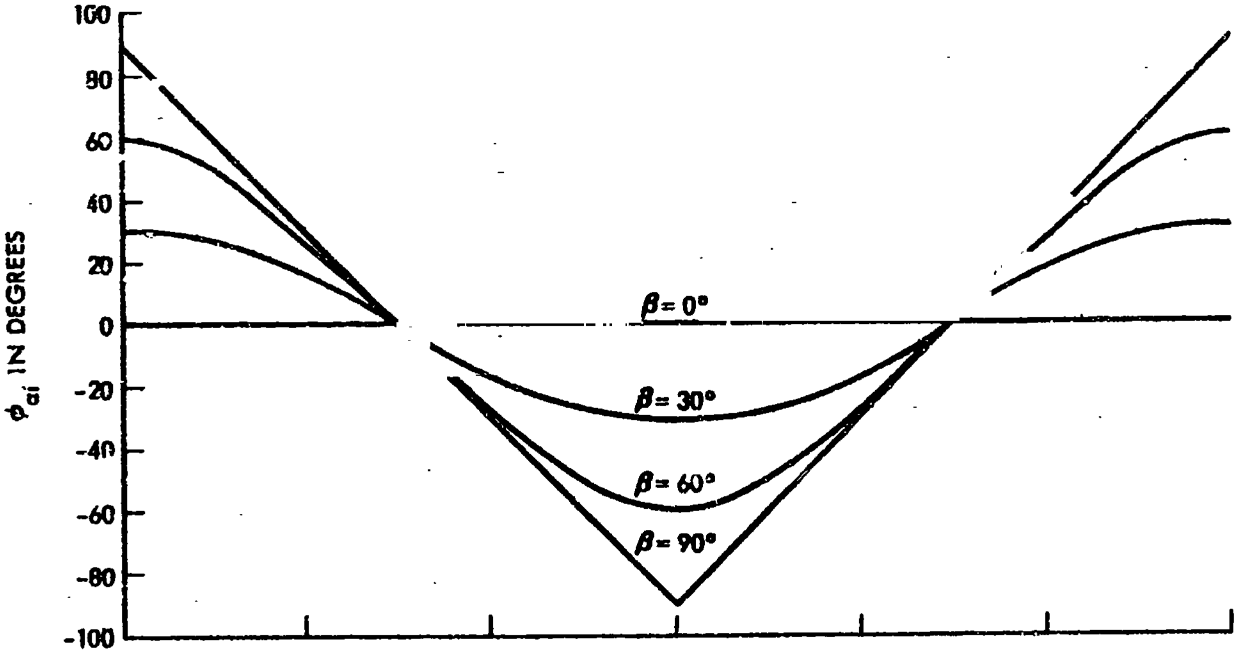


Figure 5 - IDEAL ARRAY ANGLE

infinite yaw and array rates and accelerations and infinite pitch and roll accelerations. If the control law is to be implemented, it is therefore necessary to allow yaw and solar array errors during the noon region and after an eclipse. Numerical values of the allowable error can be established by considering the degradation in power supply output due to array misalignment, and, for the OGO, temperature control considerations which dictate that the vehicle sides should not be exposed to solar radiation. For OGO, 10 minutes is allowed for yaw and array attitude recapture.

Although other considerations such as required pointing accuracy, magnitude of disturbance torques and initial attitude acquisition requirements may affect the required attitude control system dynamic performance, for a wide variety of orbits including the 24 hr synchronous, these are completely overshadowed by the noon and post eclipse requirements. For the OGO, which possesses a yaw moment of inertia of 800 slug ft^2, the noon turn requires a yaw control torque of greater than 10 in. oz. and since this torque is generated by a reaction wheel,[4] a wheel momentum storage capability of 7.5 lb. ft. sec. Furthermore during this yaw turn, the pitch and roll reaction wheels must interchange momenta requiring a torque of 6.5 in. oz. from the drive motors. The remaining gross parameters of the control system sizing are determined by disturbance torque considerations. Three disturbance torques are present; namely, solar radiation pressure, gravity gradient effects, and, for low altitude, aerodynamic moments. (Magnetic effects have been minimized in OGO.) These disturbances are adequately described elsewhere[2] and can be numerically integrated to determine the secular and cyclical components of momentum imparted to the satellite. This information is used to size the pitch and roll wheels which for OGO can absorb 1.5 ft. lb. sec. of momentum. The secular component sizes the mass expulsion system.

3. FUNCTIONAL DESCRIPTION

3.1 Torque Sources

Body control torques are provided by a three axis pneumatic system, and a three axis reaction wheel system. The two systems are operated in parallel as will be discussed in Section 3.3.

The pneumatic system is capable of providing a constant torque of either positive or negative sign about each of the three body axes. The system is used for initial orientation of the vehicle (acquisition) and to subsequently remove momentum resulting from secular disturbance torques.

Three reaction wheel systems are likewise provided, with the spin axis of each aligned with one of the three body axes. Reaction wheels are used to perform maneuvers required by the control laws discussed under Section 2. These maneuvers are cyclic over a period of one orbit. In addition, the reaction wheels provide temporary storage of momentum resulting from torques which are cyclic in inertial space, and also provide the fine control necessary to eliminate gas jet limit cycles.

3.2 Error Sensors

A system of horizon scanners is used to provide an indication of the deviation of Z_b from local vertical about two axes (pitch and roll axes) during the normal control mode of operation. The scanners will operate at altitudes from approximately 125 nautical miles to approximately 100,000 nautical miles.

Sun sensors provide an indication of the deviation of Y_a from the sun. Again two axis information is provided which is used for control during the acquisition mode of operation as well as the normal mode of operation. The sun sensors are capable of providing this information throughout a 4π steradian field of view.

3.3 Method of Control

As mentioned previously (and as depicted in Figure 6, the block diagram of the attitude control system) both the reaction wheels and the gas jets are driven in a non-linear, on-off fashion by a system which includes a dead zone and hysteresis. The reaction wheel and gas jet systems of each channel are operated in parallel, using a common error signal and common shaping. Shaping required for stability is provided by passive lead lag networks.

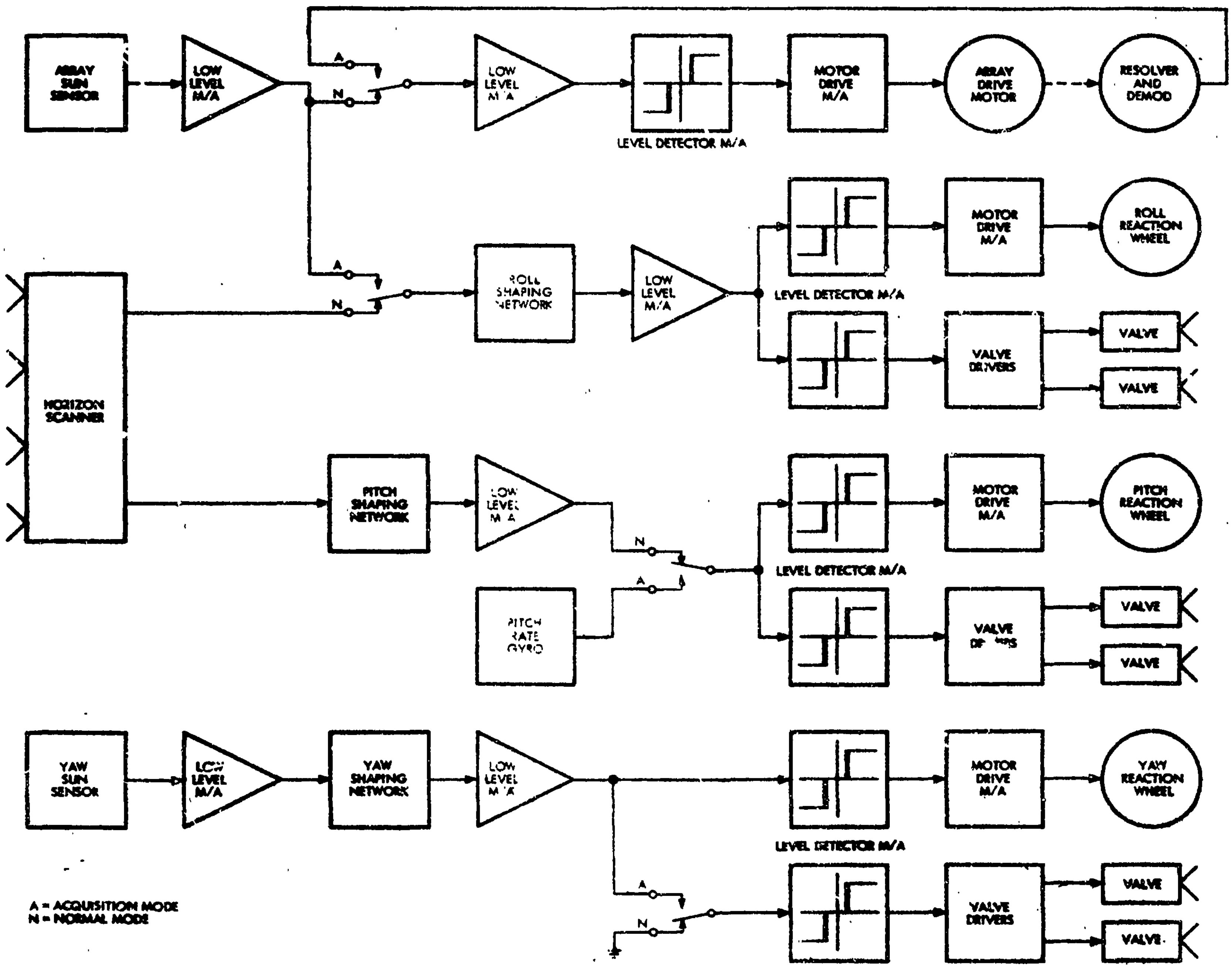


Figure 6 - BLOCK DIAGRAM OF THE ATTITUDE CONTROL SYSTEM

3.4 Modes of Operation

3.4.1 Acquisition

Again referring to Figure 6, the acquisition mode of operation is provided in order to initially stabilize the vehicle to the required references. This will be accomplished given arbitrary initial angular position with respect to these references, and initial rates limited to 1^{o}/sec or less about each of the three body axes. During this mode of operation the solar array is electrically caged in a position where $\phi_a = 0$, that is Y_a is in the direction of Y_b. The first step of the acquisition mode results in the alignment of this axis towards the sun, and the establishment of a fixed body rate about this axis. As a result of this orientation, maximum efficiency of solar power conversion is attained, and sun light is prevented from striking the satellite sides. In addition, as a result of rotation about the sun line, the field of view of the horizon scanners is swept through space and must eventually intersect the earth. When this intersection occurs, the acquisition mode of operation is terminated.

The control system configuration for this mode of operation uses the yaw sun sensor output as the error signal to the yaw channel. This signal drives the gas and reaction wheel system for this channel. The array sun sensor output is used to control the roll axis in a similar fashion, and the pitch axis gas and reaction wheel systems are driven by means of a rate gyro which has an output biased to approximately $\frac{1}{2}$ deg/sec. With this control system configuration, the solar reference will be acquired in less than 10 minutes, and the vehicle will begin searching for the earth.

3.4.2 Normal Control

After the sun acquisition mode is completed and the field of view of the horizon scanners intersects the earth in such a fashion that a proper error signal is obtained, the control system configuration is switched to the normal mode of operation. In less than 10 minutes all transients are decayed and the system is stabilized to the normal mode sun and earth references. The control system configuration at this time is as follows. The yaw sun sensor is still used to drive the yaw reaction wheel channel, however, the yaw pneumatic system is disabled. The roll and pitch outputs of the horizon scanner system are used to drive the roll and pitch control channel, respectively. Both pneumatic and the reaction wheel systems are operative. The solar array drive system is driven by the error signal from the solar array sun sensor. Barring a malfunction the system remains in this configuration for its entire life.

4. HARDWARE DESCRIPTION

4.1 Design Philosophy and Reliability

The reliability of a communication satellite attitude control system is of paramount importance for obvious reasons. The usual method of predicting the potential reliability of a circuit when no life test data are available is by a parts count and attaching to each type of component a failure rate that has been established from previous experience. This method of assessing reliability naturally presumes good circuit design, use of the best available components conservatively derated, tight quality control and appropriate packaging for the anticipated environment. The degrading effect on the reliability by the sheer number of components was immediately apparent, and the philosophy of using a bare minimum of components to do the job was adopted. In several instances, it was recognized that a significant simplification in the hardware could be realized if the control system could be operated in a different mode or with slightly less pointing accuracy. The ensuing analytical work to determine whether the proposed changes would be permissable substantially complicated the control system analysis, but the resulting simplification in the hardware has justified the effort. The most striking example of this is the on-off or bang-bang operation of the reaction wheel motors and solar array motor. The ease of controlling a motor in an on-off manner as opposed to maintaining a speed proportional to the error signal amplitude is readily apparent. Consistent with the minimum parts approach, magnetic amplifiers were selected for most of the amplification functions due to the relatively small number of components required to obtain a given amount of gain as compared to using transistor circuits. The low frequency response of the magnetic amplifier was acceptable for this application. Magnetic amplifiers are in general heavier and dissipate more power than a transistor circuit capable of comparable performance; however, for this application, the reliability advantage outweighed these disadvantages.

Another concession to reliability has been the elimination of all variable components such as potentiometers. Where adjustments in individual circuits are required, the exact value of resistance or capacitance is determined with substitution boxes, and a fixed component of nearest value is inserted.

4.2 Reference Sensors

The references used by the attitude control system are the earth and the sun. Four infrared-sensitive horizon scanners track the earth-space IR edge at 90° intervals. Signals from any three of the scanners, appropriately summed, are sufficient to develop pitch and roll error signals. The other scanner is redundant and its signal is automatically switched into the control loop whenever a detectable failure occurs in any of the other scanners. The horizon scanner is manufactured by the Advanced Technology Laboratories.

The sun sensor system is composed of fine and course sensors. The fine sensor is a silicon p-n junction device that has three outputs; two orthogonal position outputs which are dc voltages proportional to the image position on the silicon wafer, and one signal that has an output whenever the wafer is illuminated. In the normal control mode, one of the position signals is used for controlling the vehicle in the yaw axis while the other position signal is used by the solar array drive circuit to position the solar array plane normal to the incident solar radiation. The third signal is used to drive a relay that switches the control inputs between fine and coarse sensors. Pin hole optics are employed to image the sun on the wafer. The wafer is called a Radiation Tracking Transducer (RTT)[5] and manufactured by Electro-Optical Systems, Inc.

The RTT thus provides position information within a 17° half angle cone about the array normal. The remainder of the 4π steradian coverage is supplied by the coarse cells mounted at the ends of the solar panels. The coarse cells are conventional solar cells that have been preirradiated to stabilize their characteristics. The cells used to control the array are redundant to assure signal continuity when an appendage shadows one of them.

4.3 Linear Amplification and Shaping

The sun sensor signals are amplified by low-level second harmonic magnetic amplifiers with a total transimpedance greater than 10^{6} ohms, and have four control windings, which simplifies the signal summing and isolation problem. Relatively large negative feed back is employed for adjusting and stabilizing the gain and null.

The control system stability is achieved with signal shaping by the use of R-C lead-lag networks. The rather large lead time constants (≈ 50 seconds in the yaw channel and ≈ 12 seconds in the pitch and roll channel) dictated the use of non-polarized solid tantalum capacitors from size and weight considerations. Environmental testing of these networks indicates that it is feasible to employ tantalum capacitors as long as generous tolerances are allowable.

The amplified and demodulated pitch and roll error signals from the horizon scanner have enough power to drive the shaping networks directly. The signals in all three channels are heavily attenuated by their respective networks, and are again amplified by second harmonic magnetic amplifiers.

4.4 Signal Level Detection

After the second stage of linear amplification, the system is bang-bang to the torque sources. Bistable magnetic amplifiers are used to detect the various signal levels, and are "on" for any level above the trigger point and "off" for any level less than the trigger point, with a hysteresis of about 20% of the trip point for the motors and about 10% for the cold gas valve drivers. The basic bistable magnetic amplifiers trigger "on" at 50 μa signal ($\pm$ 5%) and go "off" when the signal is reduced to 40 μa. The reaction wheel channel gains are adjusted such that the trigger points correspond to $\pm 0.4^{\circ}$ vehicle attitude error in pitch and roll and $\pm 1.0^{\circ}$ in yaw. The control windings of the gas valve bistable magnetic amplifiers are in series with the control windings of the motor driver bistables, but the bias current in the former is increased by an external resistor in order that the gas valve bistable amplifiers do not trigger "on" until the error signal is a nominal 125 μa. The gas trigger points are nominally set at $\pm 1.0^{\circ}$ in pitch and roll and $\pm 2.5^{\circ}$ in yaw.

The level detector magnetic amplifier uses diodes in a parallel series quad connection to improve the reliability of the device.

4.5 Motor Switching

The three reaction wheel motors and the array drive motor are all two phase devices. The motor supply is two phase; one phase used to excite the reference winding and the other phase ($\pm 90^{\circ}$ with respect to the reference phase) is used to excite the control winding. If clockwise torque is required, the control winding is connected to the + 90° output, and the - 90° output is used for counter-clockwise torque. When the error signals are in the deadband and no motor torque is needed, both the control and reference windings are disconnected from the supply. The reference windings are disconnected not only to conserve power but to eliminate the dynamic braking effect that is undesirable in the reaction wheels.

Double-connected magnetic amplifiers are used as series ac switches to control the motor excitation. Redundant diodes are again employed for the sake of reliability. These motor drive magnetic amplifiers are not bistable by themselves but are driven by the bistable amplifiers well into saturation and far into cutoff. The use of magnetic amplifiers in the motor switching application is the greatest concession to reliability in the control system since semiconductors are much lighter and more efficient.

The array drive motor is controlled by the same type of amplifier but connected somewhat differently. Only the control winding is directly turned on by the error signal; the reference winding is subsequently turned on by rectifying and filtering part of the control winding output. When the driving bistable snaps to the "off" state, the motor control winding follows almost immediately while the reference winding remains energized until the low pass filter discharges, and this lag provides dynamic braking long enough to limit the overshoot. The difference between charge and discharge time constants permits the motor to respond to an "on" signal very fast. Dynamic braking of the array motor is desirable because there is no lead-lag stabilizing network in the signal path.

All ac power in the control system is square wave, including the low level magnetic amplifier excitation.

4.6 Reaction Wheels

As mentioned previously, the reaction wheels are two phase motors and have induction motor speed-torque characteristics. The devices are "inside out" motors with the stator windings inside and the rotor containing the squirrel cage windings outside. This construction allows the maximum rotor moment of inertia for a given case size. The entire assembly is hermetically sealed and pressurized to about one half atmosphere as a compromise between windage power losses and bearing lubricant retention.

A permanent magnet pulse tachometer is used to telemeter wheel speed and direction of rotation. Both the amplitude and frequency of the pulses vary with speed, and the polarity of the pulse indicates direction of rotation. The frequency of the pulses is used to develop an analog voltage proportional to speed.

It should be emphasized that the tachometers are not used in the control loop. An electrical failure in the tachometer or signal conditioning circuitry will only result in loss of data and not affect the control system operation.

The reaction wheels are manufactured by the Bendix Corporation.

4.7 Pneumatic Subsystem

The gas (Argon) is stored in a spherical tank at an initial pressure of about 3,000 psi. A pressure regulator maintains the low pressure manifold at about 50 psi, and contains filters and a relief valve. The low pressure gas is piped to the six solenoid valves, also containing filters, and the discharge of the valves are through tubes out the gas booms to nozzles where 0.05 pounds of force is generated per nozzle. Between each solenoid valve and its respective nozzle a non in-line pressure switch is plumbed in to provide telemetry with gas usage data. Since the duration of the gas pulse in normal control is shorter than the telemetry sampling period, flip flops are used to store the information until interrogated by telemetry. Also telemetered are the high and low gas pressures as well as the gas bottle temperature. From these data it is possible to determine the amount of remaining gas. The tank is filled through a manually operated valve when the vehicle is on stand.

The solenoid valves are energized directly from the vehicle battery supply (nominal 28V) and controlled by series power silicon transistors. The transistor switches are normally biased off and turned on by the gas bistable level detectors. The yaw gas is not used after acquisition since it is not required for normal control, and gas consumption would be materially increased because large yaw error signals are possible during the noon and post eclipse maneuvers.

4.8 Array Drive Mechanism

The array shaft is rotated by an electromechanical drive in which an electric motor and gear train are coupled to the array shaft through a hermetic seal. The output number of this drive is a large cone angle bevel gear. This gear is held irrotational and is mounted in skew-axis bearings so that it meshes with a mating gear at only one point on the pitch line. The input gear is thus constrained to "wabble" as the skew-axis is rotated about the output axis. The output gear is then smoothly and efficiently turned by an amount equal to the angle subtended by the difference in number of teeth between the input and output gear for each revolution of the point of mesh. A very large reduction is thus gained in the output wabble gears (99:1). The drive is designed so that the array shaft is a large tube that runs directly through the drive. Through this shaft the wires from the sun sensors and solar cells are routed.

The prime mover for the drive mechanism is a specially designed size 11 servo motor. The overall gear reduction from the motor to the output shaft is 24,000 to 1. The unit is capable of output torques in excess of 100 inch - pounds.

Since no slip rings are used, a cable wrap-up mechanism is necessary to pay out and take in the wires without fouling as the shaft array shaft rotates. The wrap up mechanism requires a substantial torque which makes torque motors unattractive for this application.

A cam and limit switches are provided to prevent overtravel of the array shaft. A special pancake resolver is fixed to the shaft and vehicle body to provide telemetry with shaft angle data as well as caging the array during acquisition.

4.9 Pitch Rate Gyro

The pitch rate gyro is used during the acquisition sequence to cause the vehicle to slowly rotate about the pitch axis which will ultimately enable the horizon scanner heads to see the earth. The rate gyro is a temperature compensated spring restrained device with a dc torquer and a two phase motor. A bias current is introduced into the torquer winding such that the output of the rate gyro causes the pitch gas system and reaction wheel to null any initial rates to the bias rate ($\approx 0.5^{\circ}$/sec.). The gyro pickoff signal is amplified by a conventional transistor amplifier and demodulated with a diode bridge demodulator. Both the spin motor rotation detector output and the demodulator output are telemetered.

The gyro is started prior to launch and remains on until acquisition is complete. At this time, the gyro is turned off to conserve power and minimize bearing wear, but is turned on again in event of loss of attitude reference.

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